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RESEARCH MEMORANDUM

EFFECT OF FUEL-AIR RATIO CONCENTRATION IN COMBUSTION ZONE
ON COMBUSTION PERFORMANCE OF A 16-INCH RAM-JET ENGINE

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RESEARCH MEMORANDUMEFFECT OF FUEL-AIR RATIO CONCENTRATION IN COMBUSTION ZONE
ON COMBUSTION PERFORMANCE OF A 16-INCH RAM-JET ENGINE

By A. J. Cervenka, D. W. Bahr, and E. E. Dangle

SUMMARY

The effect of the fuel-air ratio concentration in the wake of a simple-baffle flame holder in a 16-inch ram-jet engine was determined. The fuel-air ratio concentration was found to be considerably higher under burning conditions than that measured under nonburning conditions. Temperature and fuel-air ratio surveys in the combustion zone of the ram-jet engine indicated the need for controlling fuel-air mixing in this zone.

A sloping-baffle combustor configuration was investigated in which the distribution of fuel-air mixture in the combustion zone was mechanically controlled. This design gave combustion efficiencies of 90 percent or greater over a range of fuel-air ratios from 0.010 to 0.045 at the following inlet conditions: pressure, about 1 atmosphere; temperature, 600° F; velocities, 210 to 260 feet per second.

INTRODUCTION

This experimental investigation is part of a ram-jet-combustor design program being conducted at the NACA Lewis laboratory. The objective of this program is the attainment of combustor designs and design criteria which will permit efficient and stable ram-jet combustion over wide ranges of fuel-air ratios and combustor-inlet conditions.

In a previous project reported in reference 1, it was found that pressure pulsations due to combustion increased the fuel spreading in the prereaction zone of a combustor, resulting in a more rapid dilution of fuel-air mixtures than that for the nonburning case. By mechanically controlling the fuel-air spreading, combustion performance was improved.

The effect of combustion on fuel-air mixing in the combustion zone has been investigated in this project in which the two-fold objective is:

- (1) To investigate fuel-air ratio distribution in the wake of a simple-baffle flame holder as a possible source of inefficiency present with this type of combustor at lean fuel-air ratios

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- (2) To investigate the performance of a combustor configuration designed to control fuel-air mixing in the combustion zone

The research was conducted with a 16-inch-diameter ram-jet combustor at inlet conditions corresponding to a flight Mach number of 2.9, an altitude of 67,000 feet, and a diffuser pressure recovery of 70 percent. Combustion efficiencies were determined at these inlet conditions over a range of fuel-air ratios. The fuel-air ratio surveys in the combustion zone were made under burning and nonburning conditions with radially movable sampling probes located at various stations along the combustor axis. Fuel-air ratios were determined with an NACA mixture analyzer. Temperature surveys were made at the same stations as the fuel-air surveys.

Since these tests are intended to indicate trends in performance with combustor designs that will be investigated further at more severe operating conditions, the results should be treated as preliminary data. Similarly, since sampling techniques that give representative samples in the combustion zone have not been fully developed, these data are intended to indicate trends in fuel-air ratio distribution and not absolute values.

APPARATUS AND PROCEDURE

The engine and test installation for this investigation were the same as those used in reference 2. A sketch of the engine is shown in figure 1 and of the test installation in figure 2. A sketch which gives the location of sampling stations in the flame-holder region is shown in figure 3.

Flame holders. - The two flame-holder configurations used are shown in figures 4 and 5. The simple-baffle flame holder shown in figure 4 consisted of six radial V-gutters with a total over-all blocked area of 37 percent. The open ends of the V-gutters measured $1\frac{1}{2}$ inches across.

The sloping-baffle flame holder shown in figure 5 consisted of two sets of U-shaped baffles separated by a conical section. The six baffles in the primary zone and the 12 baffles in the secondary zone were inclined at a 30° angle to the combustor axis. The flame-holder open area projected on a surface parallel to the baffles was 100 percent of the combustion-chamber frontal area.

Control sleeve. - The fuel-mixing control sleeve used with the sloping-baffle configuration was 10 inches in diameter and extended from the fuel injectors to the flame holder. The sleeve intercepted approximately 20 percent of the total engine-air mass flow and ducted this air into the primary combustion zone.

Fuel-injector systems. - Fuel was injected through six nozzles located $17\frac{1}{8}$ inches upstream of the radial V-gutter flame holders. The nozzles were rated at 0.5 gallon per minute at a pressure differential of 100 pounds per square inch and were located in line with the flame holders.

In the sloping-baffle flame-holder installation, fuel was injected through six hollow-cone nozzles rated at 0.5 gallon per minute into the inner fuel zone and through 16 nozzles into the outer zone. The six nozzles were located in line with the primary-zone baffles. The 16 nozzles were each rated at 0.36 gallon per minute at a pressure differential of 100 pounds per square inch. The fuel injectors were located approximately 17 inches upstream of the flame holder.

Fuel. - The properties of MIL-F-5624A grade JP-4 fuel used as both primary and pilot fuel are given in table I.

INSTRUMENTATION AND METHODS

Operating conditions. - The ram-jet combustor was operated over the following inlet conditions:

Inlet-air static pressure, in. Hg abs	32 to 36
Inlet-air temperature, °F	600
Inlet-air velocities, ft/sec	210 to 260

These values correspond to the combustor-inlet conditions in a ram-jet engine flying at a Mach number of 2.9 at an approximate altitude of 67,000 feet, with a diffuser pressure recovery of 70 percent.

Combustion efficiency. - Combustion-efficiency data were limited to a fuel-air ratio range from 0.010 to 0.045. This range of operating conditions was imposed by calorimeter limitations rather than combustion limitations. Combustion temperatures were determined by a heat-balance system. At a given engine operating condition, the quench-water flow was adjusted to a value insuring complete vaporization of the water. The water mass flow was varied so that outlet temperatures of 600° to 900° F were maintained at the thermocouple station. The total enthalpy change of the fuel, air, quench water, and engine cooling water was divided by the heating value of the fuel to obtain combustion efficiency.

At fuel-air ratios leaner than 0.014, combustion efficiencies were determined by comparing the temperature rise across the combustor as determined by temperature surveys with the theoretical temperature rise.

Fuel-air sampling. - Fuel-air samples were taken under burning and nonburning conditions at a station 5 inches upstream of and in line with the flame holder, at three stations in the wake of the simple-baffle flame holder, and at a station circumferentially midway between two baffles. These surveys were made from the combustor wall radially toward the center of the combustor, a distance of approximately 5 inches. The over-all fuel-air ratio was held at a constant value of 0.017 during these tests.

Three types of sampling probe were employed in the fuel-air distribution studies. Fuel-air samples upstream of the flame holder were obtained with a 1/8-inch-diameter probe directed into the air stream. A 1/4-inch open-end tube was used to obtain samples inside of the V-gutter baffle. Probes located in the wake of the baffle and between baffles consisted of 1/4-inch closed-end tubes with sampling orifices on the sides of the tubes directed upstream. The samples were analyzed by means of an NACA fuel-air ratio mixture analyzer.

Temperature surveys. - Exhaust-gas temperatures were measured at the three stations immediately downstream of the simple-baffle flame holder and at four stations located 30, 51, 60, and 75 inches downstream of and in line with a baffle. Temperatures were measured at the combustor exit with the sloping-baffle configuration.

Temperature surveys were made with radially movable, unshielded, chromel-alumel thermocouples.

Pressure pulsations. - Combustion-chamber pressure pulsations were determined with a diaphragm pickup connected to a strain analyzer and ink-recording oscillograph.

RESULTS AND DISCUSSION

Distribution Data

Three fuel-air distributions, 5 inches upstream of a flame holder, are presented in figure 6. The fuel distribution with preheated fuel was more uniform than with nonpreheated fuel because of the higher fuel pressures with preheated fuel. These results also show that the fuel distribution in the precombustion zone was the same under both burning and nonburning conditions. Previous studies, made with a 16-point fuel injector in this engine and reported in reference 1, showed that burning markedly altered the precombustion fuel distribution. This effect was attributed to the increased pressure pulsations which resulted from the burning process, as noted by comparing figures 7(a) and 7(b). With the six-point fuel-injector configuration used in the present investigation, however, burning was found to occur with no appreciable pressure pulsation, as shown in figure 7(c).

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The results of fuel-air ratio surveys taken radially at three stations in the wake of a flame-holder baffle are presented in figure 8. These profiles were determined with nonpreheated and preheated fuel and under burning and nonburning conditions. As shown by comparing figures 6 and 8, the flame holder tended to distribute fuel radially behind it. Also, figure 8 shows that fuel-air ratios obtained behind the flame holder under burning conditions were considerably higher than those obtained under nonburning conditions, although no such differences were found in the precombustion zone.

The following explanations are given for the difference in fuel-air concentrations under burning and nonburning conditions:

(1) Liquid fuel droplets which impinge on a heated baffle evaporate and produce locally rich mixtures in the wake of the baffle as shown in reference 3. An indication that this effect is of some importance is seen by comparing the fuel-air distributions downstream of the flame holder with nonpreheated and preheated fuel under burning and nonburning conditions.

(2) The size of eddies downstream of bluff bodies was found, in reference 4, to be smaller under burning than nonburning conditions. The stronger eddy action under nonburning conditions may tend to dilute the fuel-air mixture downstream of a baffle.

(3) There is a shift in the air flow approaching a flame front as shown in reference 4. This shift in air flow may produce a locally rich fuel-air concentration since fuel droplets would not be diverted because of their greater momentum.

(4) A nonrepresentative fuel-air sample may be obtained in the eddy region downstream of a baffle because of the flow of fuel-air mixture parallel to the plane of the probe entrance. This effect was believed to be slight since fuel-air samples obtained with sampling orifices directed either axially upstream or radially showed the same differences in distribution under burning and nonburning conditions.

In order to determine the effect of burning on the circumferential fuel-air ratio distribution, radial surveys were taken midway between two flame holders. These results are shown in figure 9. The profiles with burning are again higher than those without burning, although all four of the distributions are below the measured over-all fuel-air ratio of 0.017.

The small differences in the distributions at this station probably result from the effect of burning on eddy size. More air flow parallel to the plane of the sampling orifice would be expected at this station in the nonburning case than with burning.

Two radial temperature surveys, taken in the wake of a flame holder, are shown in figure 10(a). Temperature profiles at four distances downstream of the flame holder and in line with it are presented in figure 10(b). The high temperatures found at the flame holder substantiate the high fuel-air ratios that were determined under burning conditions in this region. The surveys downstream of the flame holder indicate that, with this flame holder and fuel-injector configuration, a large part of the burning occurred in an annular area near the outer wall of the combustion chamber.

In summary, then, the fuel-air ratio surveys upstream of and behind the radial baffles demonstrated that, both without and with combustion, fuel arriving at the baffle was distributed radially by the baffle. Also, the fuel-air ratio surveys behind the radial baffle demonstrated that, with combustion, fuel tended to concentrate behind the baffle and continued to be distributed radially by the baffle. The temperature surveys downstream of the radial baffles support the observations made with fuel-air ratio surveys. Because the fuel-air ratios in the very important flame-stabilizing and flame-propagating zone immediately downstream of a flame holder appear to be strongly affected by the combustion process, the implication is strong that the distribution of the combustible mixture in the zone immediately downstream of flame holders should be mechanically controlled, if a preferred mixture composition is to be maintained in that zone.

Sloping-Baffle Flame Holder

The sloping-baffle flame holder was designed to provide control of fuel-air mixing and also to provide control of mixing of unburned with burned products downstream of the point of initiation of combustion. Combustion is initiated in the wake of the upstream set of baffles and substantially completed in the shielded region downstream of these baffles. At lean fuel-air ratios, combustion occurs only in the primary zone and dilution with secondary air takes place downstream of the shielded region. A smooth, continuous, flame path from the primary to the secondary burning zone is provided for rich fuel-air ratio operation. The use of a sloping baffle and conical shielded zone provides an expanding volume for the primary combustion region, thereby maintaining a low flow velocity which permits combustion to be completed in a relatively short length.

The combustion performance of this configuration is shown in figure 11. A combustion-efficiency level of 90 percent or greater was obtained over a range of fuel-air ratios from 0.010 to 0.045 with a dual fuel-injection system. The data limits of the lean and rich fuel-air ratios in this figure were imposed by the test facility and are not combustor operating limits.

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A comparison of the combustion performance of the sloping-baffle configuration with the performance of three radial baffle configurations reported in reference 2 is made in figure 12. The six-point fuel injector was used in all the radial baffle configurations summarized in this figure. The performance of a radial baffle configuration with optimum radial injector location but with uncontrolled fuel-air mixing in the prereaction zone was improved by the use of control sleeves in this mixing zone. A further improvement in performance at lean fuel-air ratios was achieved with the sloping-baffle design. This improvement is believed to be primarily due to the fuel-air mixing control in the combustion zone in addition to prereaction zone control employed in this design. This mixing control principle is similarly employed in can-type combustors, which will be investigated in a continuation of the present study. However, the desirable features of the simple-baffle flame holder have been retained in the sloping-baffle configuration.

An indication of the effectiveness of the combustion-zone mixing control obtained with the sloping-baffle design is shown in figure 13. The temperature profile at the combustor-exit stations shows that, at lean over-all fuel-air ratios, a locally rich fuel-air mixture was concentrated in the center of the duct. With the radial baffle design, combustion took place over a larger cross-sectional area, as was shown in figure 10(b) by the high gas temperatures near the combustor wall and the lower temperatures in the core.

SUMMARY OF RESULTS

1. The fuel-air ratio concentration in the wake of a simple-baffle flame holder was found to be considerably higher under burning conditions than that measured under nonburning conditions.

2. A sloping-baffle combustor design in which fuel-air mixing in the combustion zone was controlled gave combustion efficiencies of 90 percent or greater over a range of fuel-air ratios from 0.010 to 0.045.

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REFERENCES

1. Cervenka, A. J., and Dangle, E. E.: Effect of Fuel-Air Distribution on Performance of a 16-Inch Ram-Jet Engine. NACA RM E52D08, 1952.
2. Dangle, E. E., Cervenka, A. J., and Bahr, D. W.: Effects of Fuel Temperature and Fuel Distribution on the Combustion Efficiency of a 16-Inch Ram-Jet Engine at a Simulated Flight Mach Number of 2.9. NACA RM E52J14, 1953.
3. May, Walter G., and Maddocks, Frank E., Jr.: Flame Stabilization in Air/Fuel-Spray Mixtures at High Velocity. M.I.T. Meteor Rep. No. 54, Fuels Res. Lab., Apr. 1950.
4. Williams, G. C., Hottel, H. C., and Scurlock, A. C.: Flame Stabilization and Propagation in High Velocity Gas Streams. Third Symposium on Combustion and Flame and Explosion Phenomena, The Williams & Wilkins Co. (Baltimore), 1949, pp. 21-40.

TABLE I. - SPECIFICATIONS AND ANALYSIS OF MIL-F-5624A
GRADE JP-4 ENGINE FUEL



	Specifications	Analysis
A.S.T.M. distillation		
D 86-46 (°F)		
Initial boiling point		140
Percentage evaporated		
5		199
10	250 (max)	224
20		250
30		270
40		290
50		305
60		325
70		352
80		384
90		427
Final boiling point	550 (max)	487
Residue (percent)	1.5 (max)	1.2
Loss (percent)	1.5 (max)	0
Aromatics (percent by volume) A.S.T.M. D875-46T	25 (max)	
Specific gravity °A.P.I.	40 (min), 58 (max)	0.765
Reid vapor pressure (lb/sq in.)	2.0 (min), 3.0 (max)	2.7
Hydrogen-carbon ratio		0.169
Net heat of combustion (Btu/lb)	18,400 (min)	18,700

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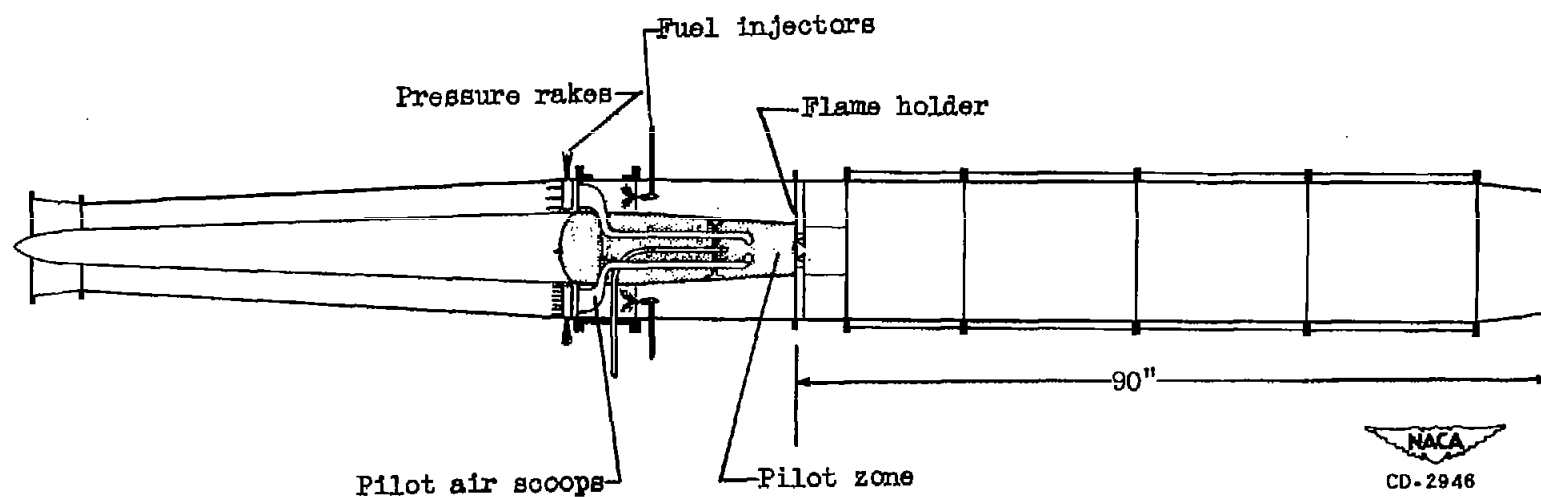


Figure 1. - Sketch of 16-inch ram-jet engine showing position of fuel injectors, flame holder, and pilot.

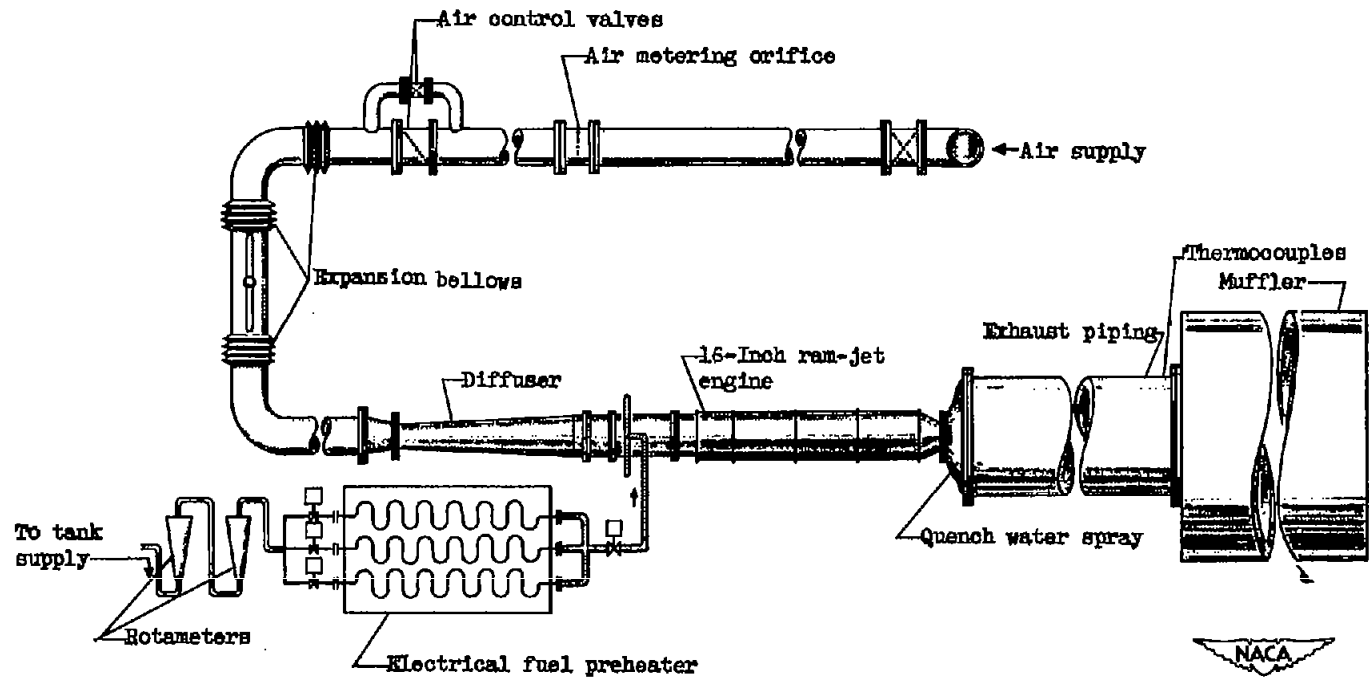


Figure 2. - Installation of 16-inch ram-jet engine.

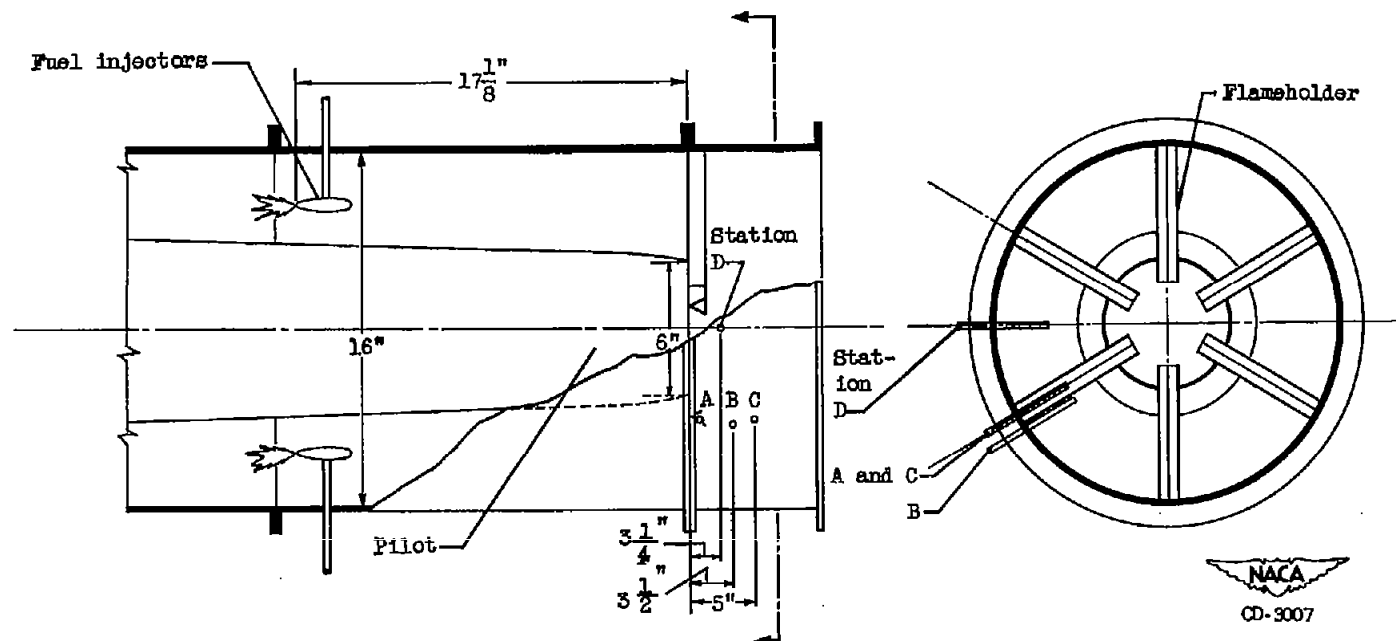


Figure 3. - Location of sampling stations in combustion zone.

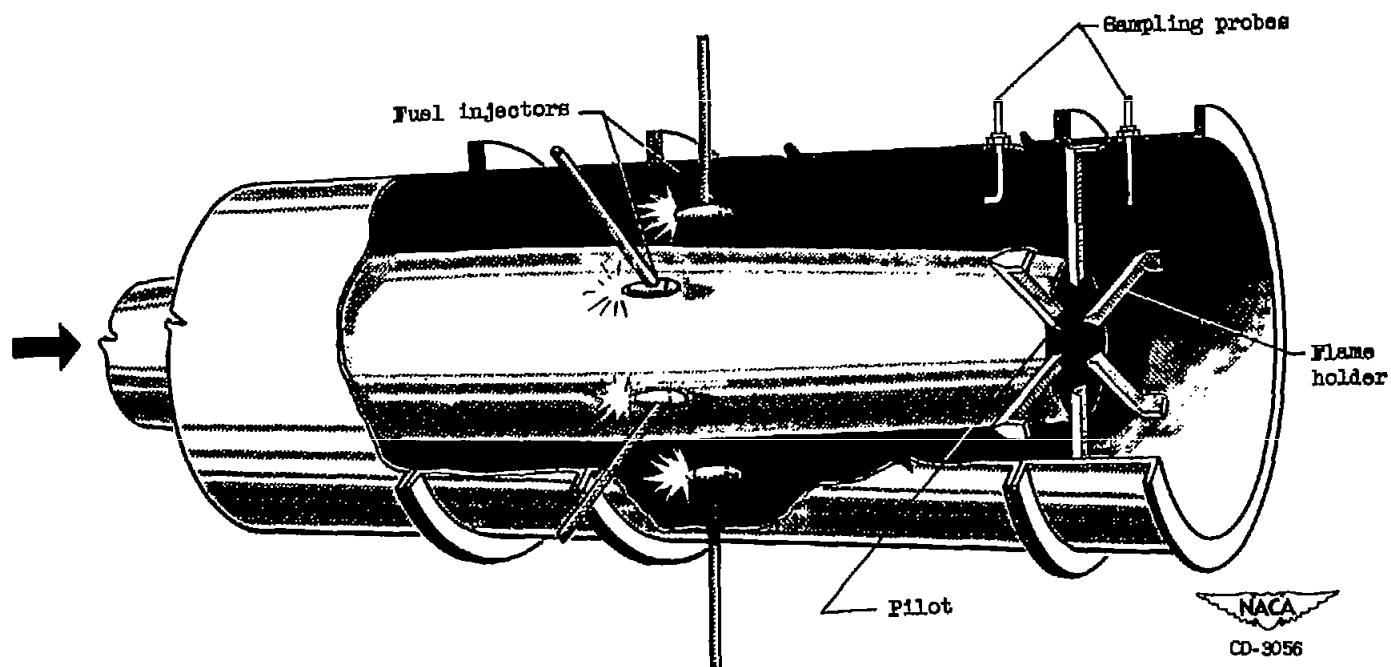


Figure 4. - Radial V-gutter flame-holder configuration.

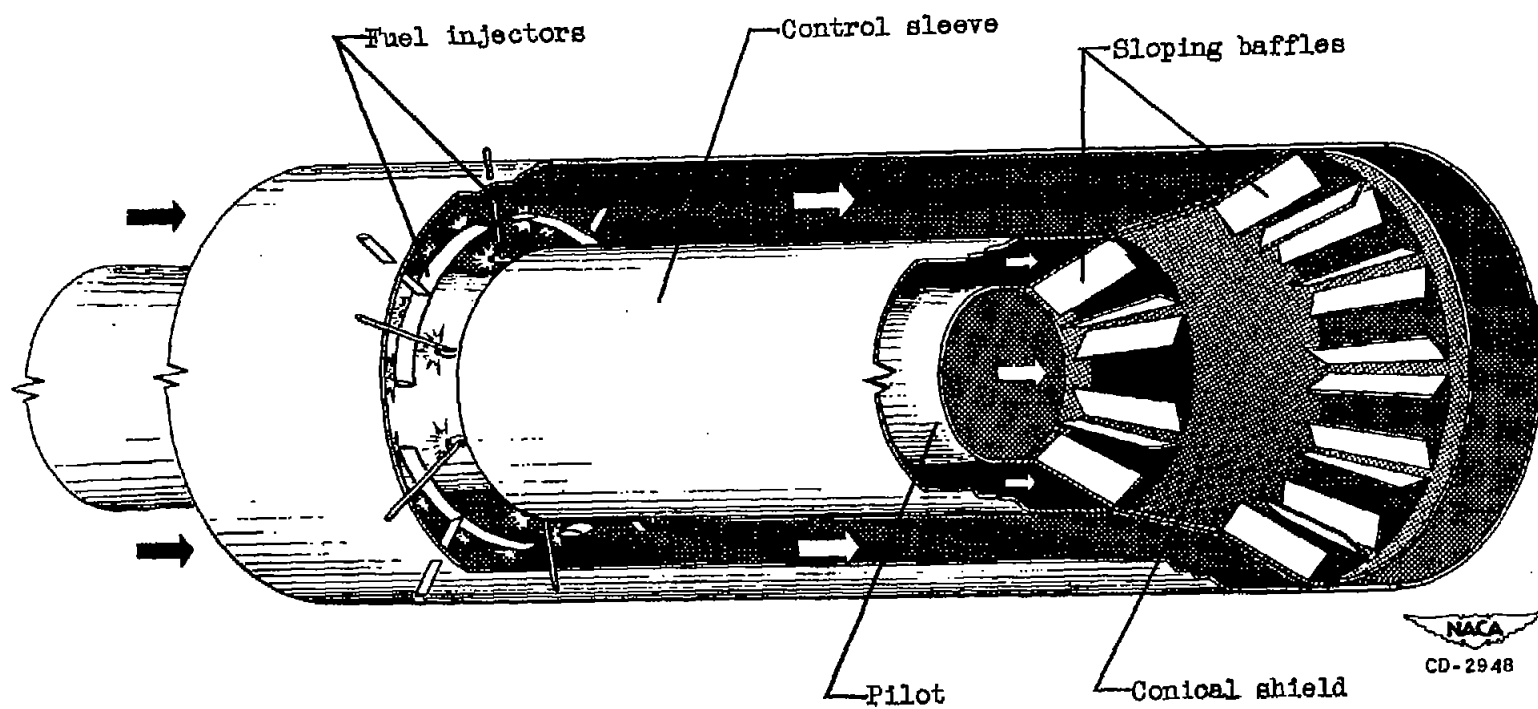


Figure 5. - Sloping-baffle flame-holder configuration.

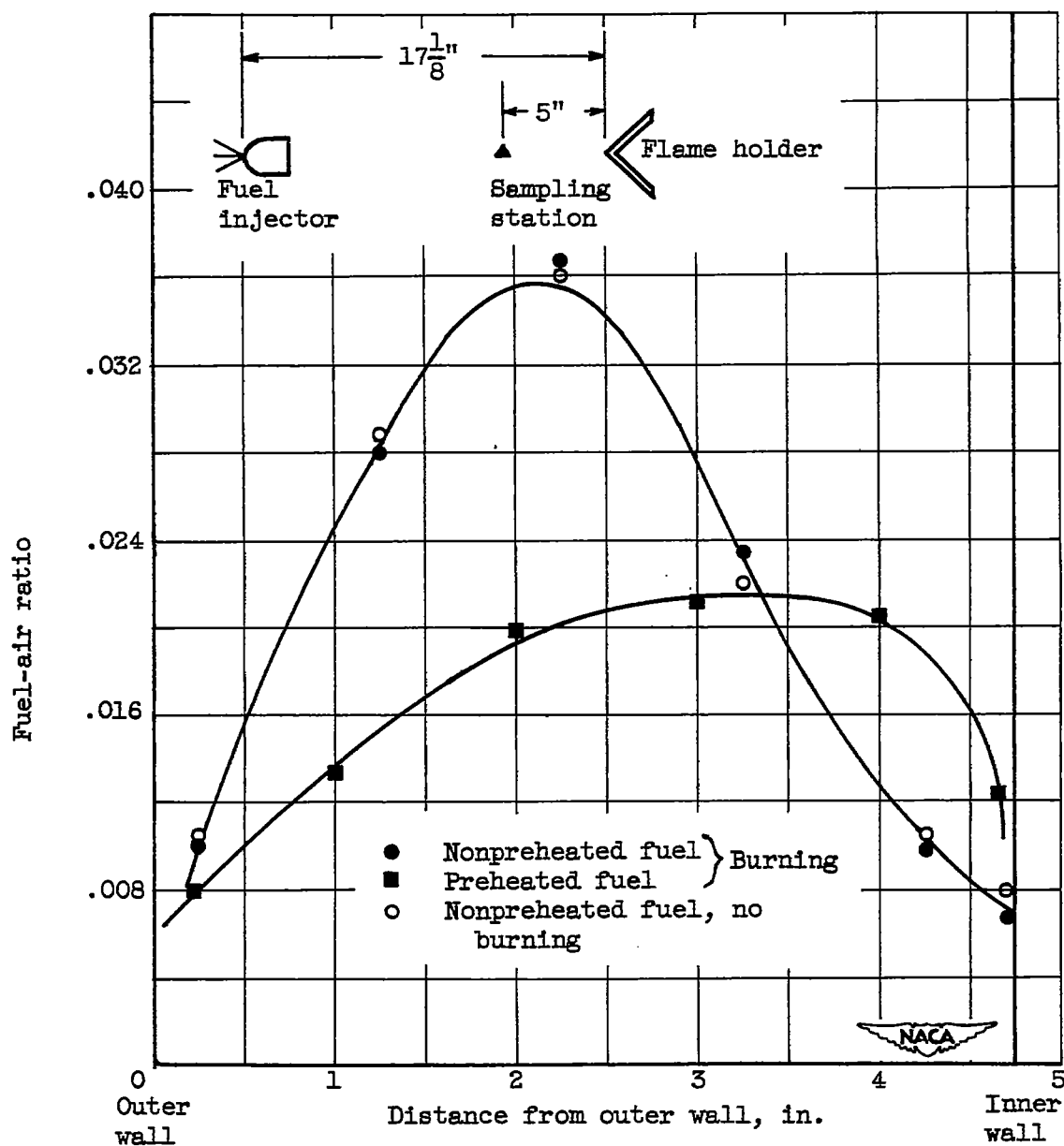
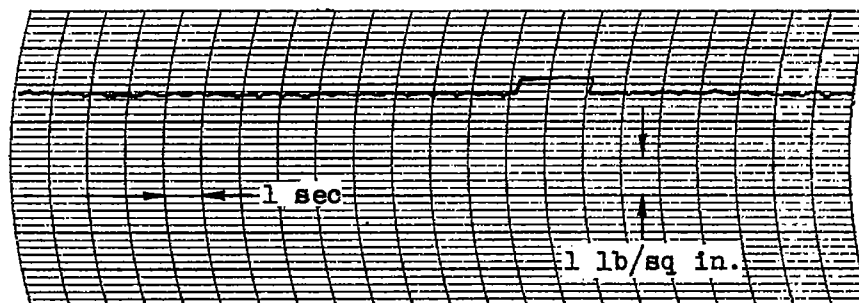
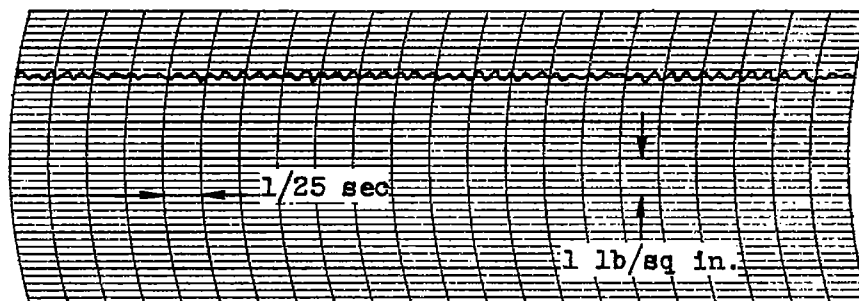


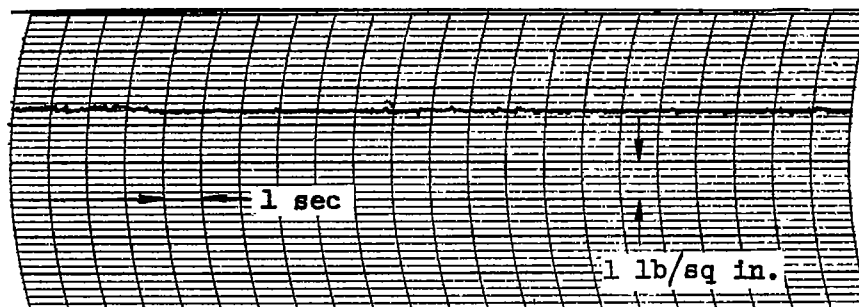
Figure 6. - Fuel-air ratio distributions upstream of flame holder for MIL-F-5624A grade JP-4 fuel. Over-all fuel-air ratio, 0.017; inlet-air temperature, 600° F; velocity, 230 to 260 feet per second; pressure, 31 to 35 inches of mercury absolute.



(a) Simple-baffle flame holder; no burning (ref. 1).



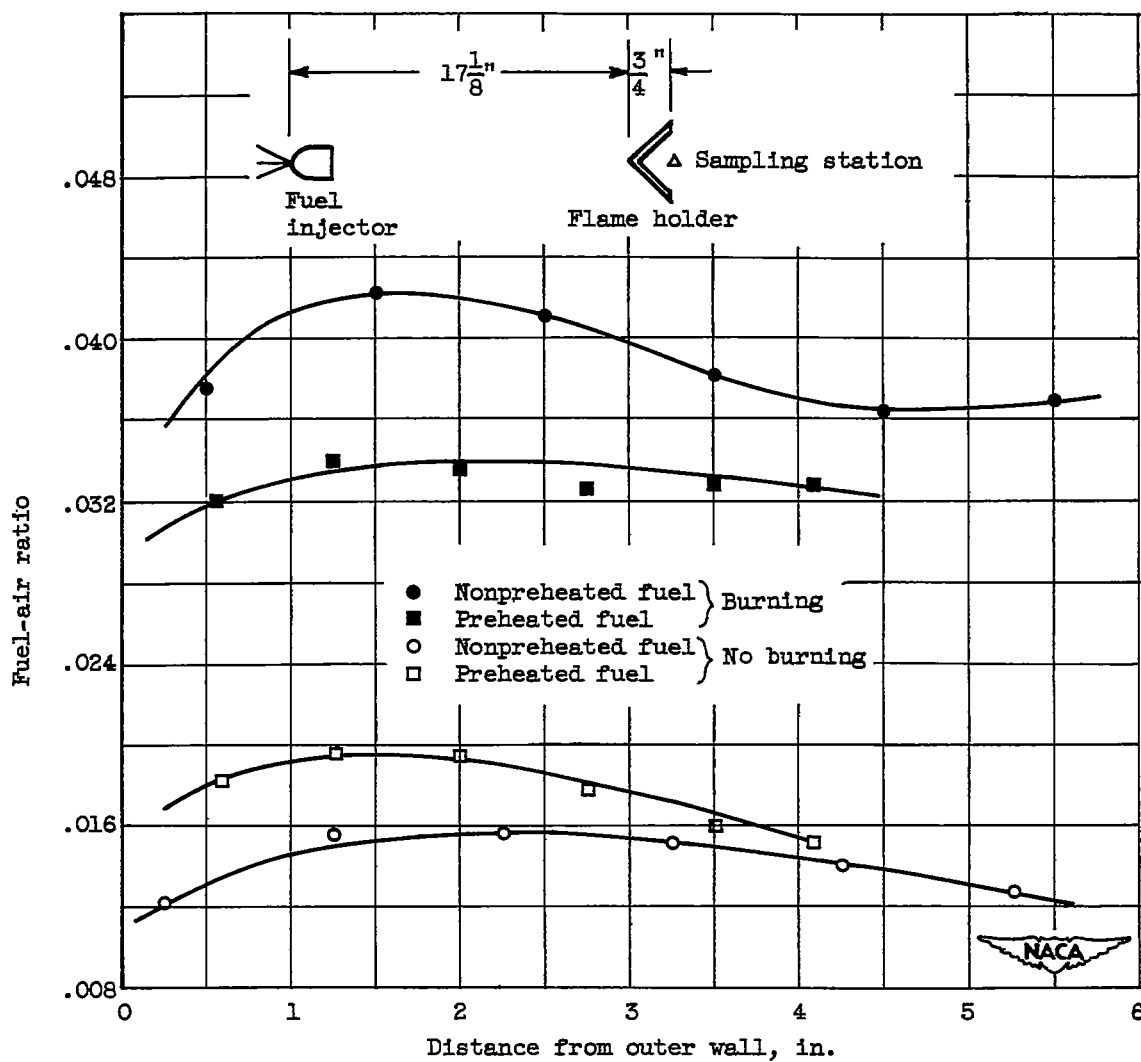
(b) Simple-baffle flame holder, 16-point fuel injector; burning (ref. 1).



(c) Simple-baffle flame holder, six-point fuel injector; burning.

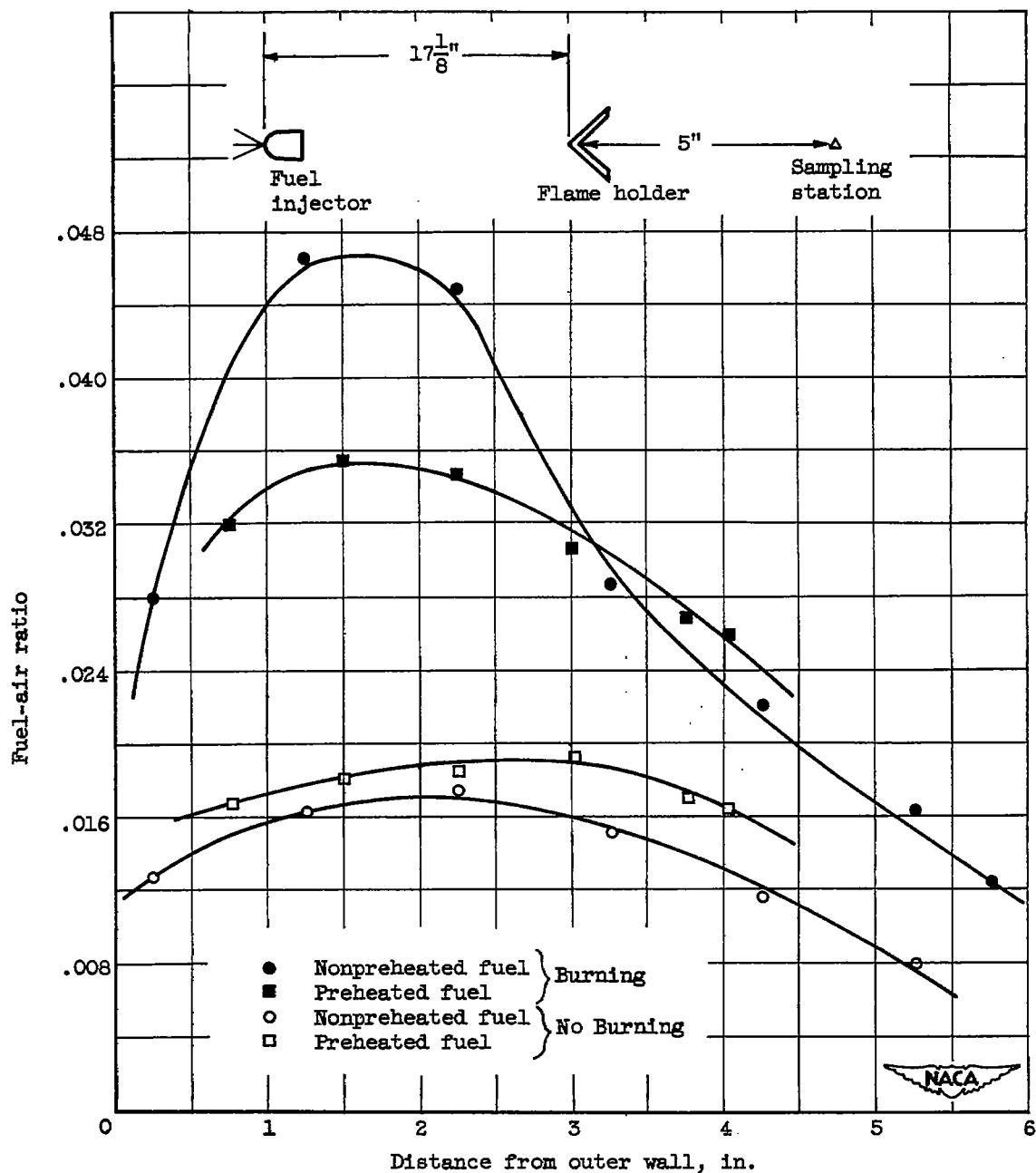


Figure 7. - Combustor-inlet pressure pulsations.



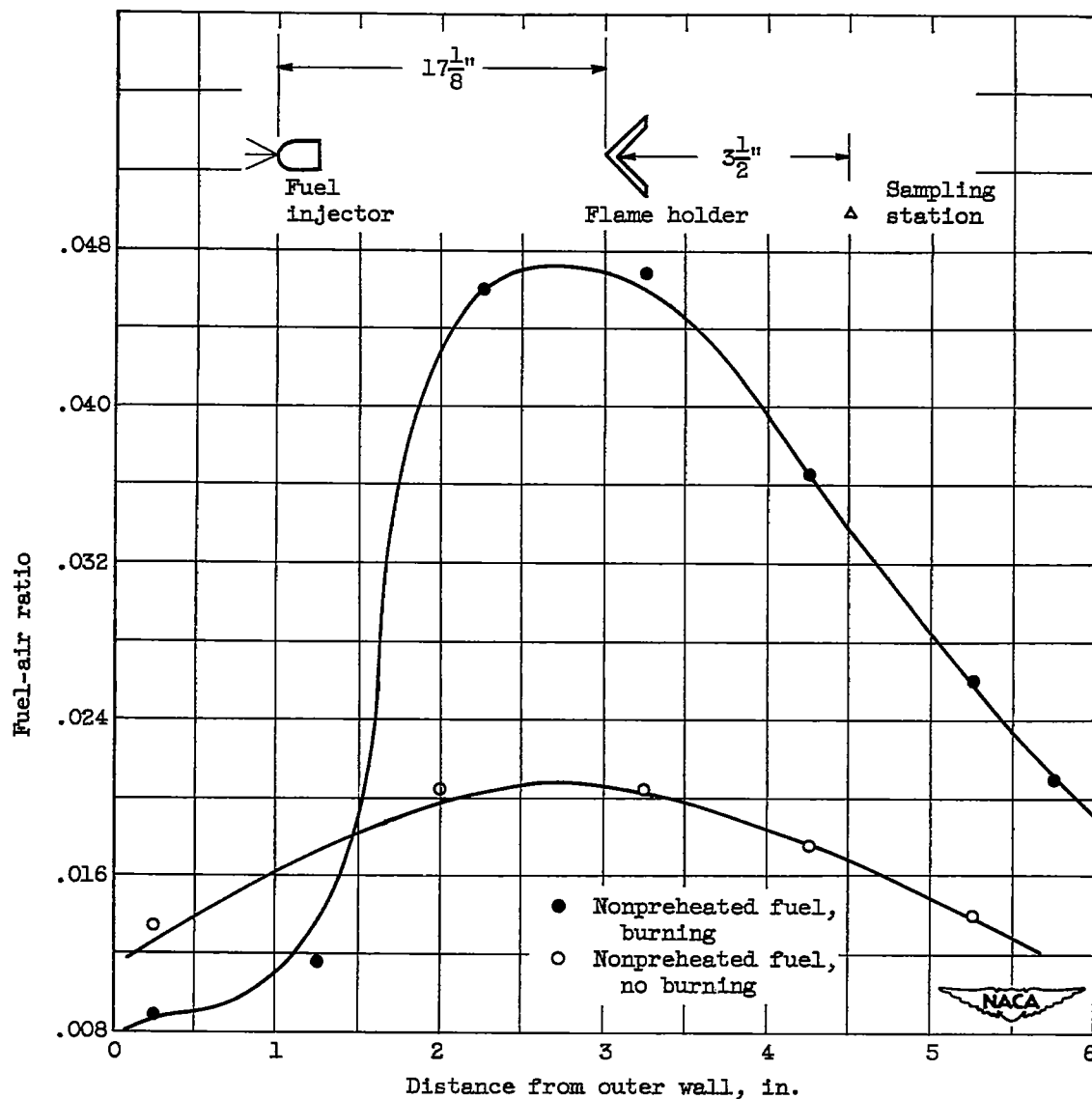
(a) Sampling station directly behind flame holder.

Figure 8. - Fuel-air ratio distributions downstream of flame holder for MIL-F-5624A grade JP-4 fuel. Over-all fuel-air ratio, 0.017; inlet-air temperature, 600° F; velocity, 230 to 260 feet per second; pressure, 31 to 35 inches of mercury absolute.



(b) Sampling station 5 inches downstream of flame holder.

Figure 8. - Continued. Fuel-air ratio distributions downstream of flame holder for MIL-F-5624A grade JP-4 fuel. Over-all fuel-air ratio, 0.017; inlet-air temperature, 600° F; velocity, 230 to 260 feet per second; pressure, 31 to 35 inches of mercury absolute.



(c) Sampling station $3\frac{1}{2}$ inches downstream of and off-center from flame holder.

Figure 8. - Concluded. Fuel-air ratio distributions downstream of flame holder for MIL-F-5624A grade JP-4 fuel. Over-all fuel-air ratio, 0.017; inlet-air temperature, 600° F; velocity, 230 to 260 feet per second; pressure, 31 to 35 inches of mercury absolute.

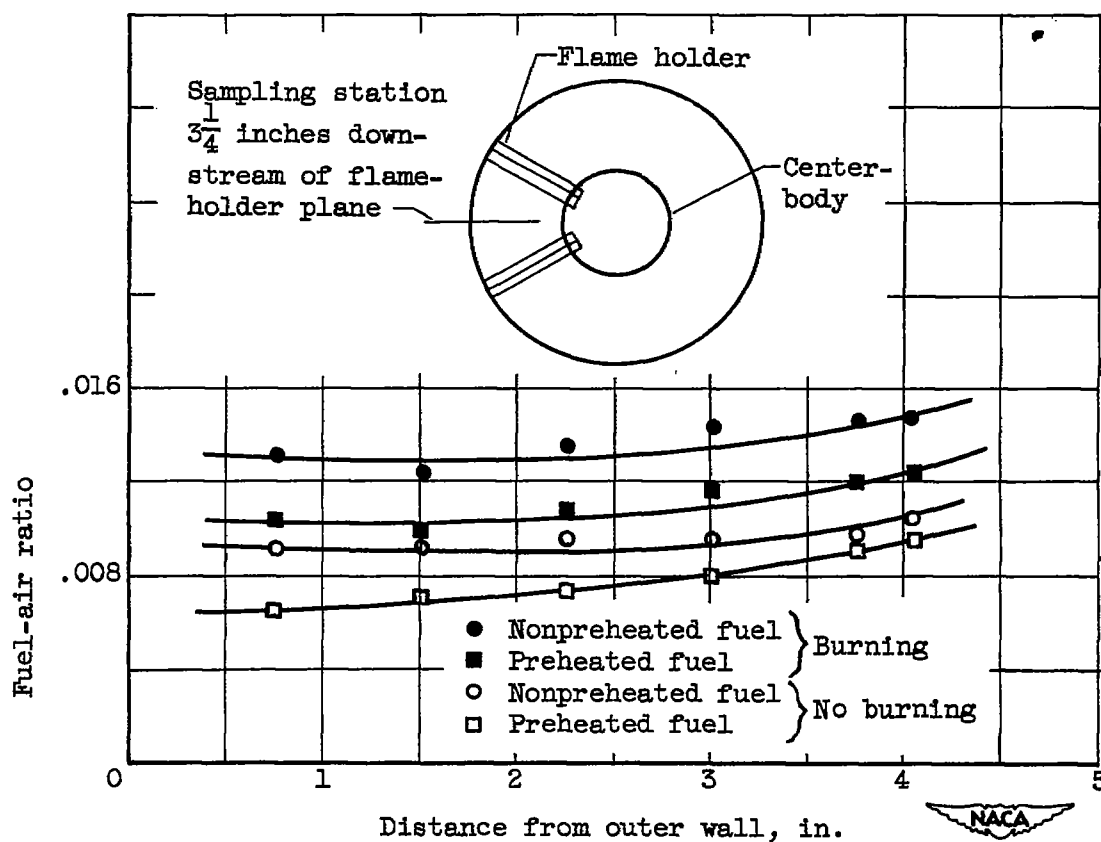
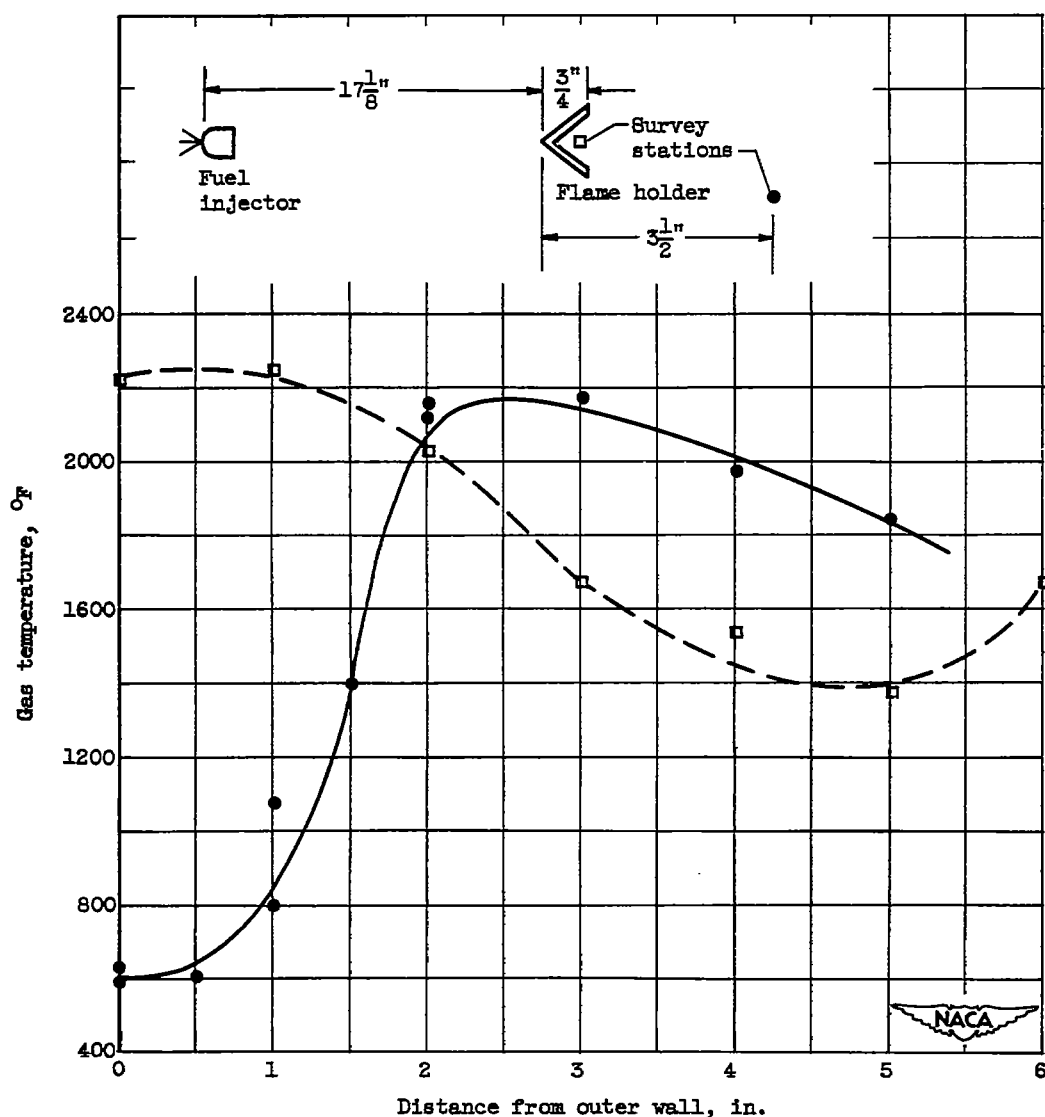
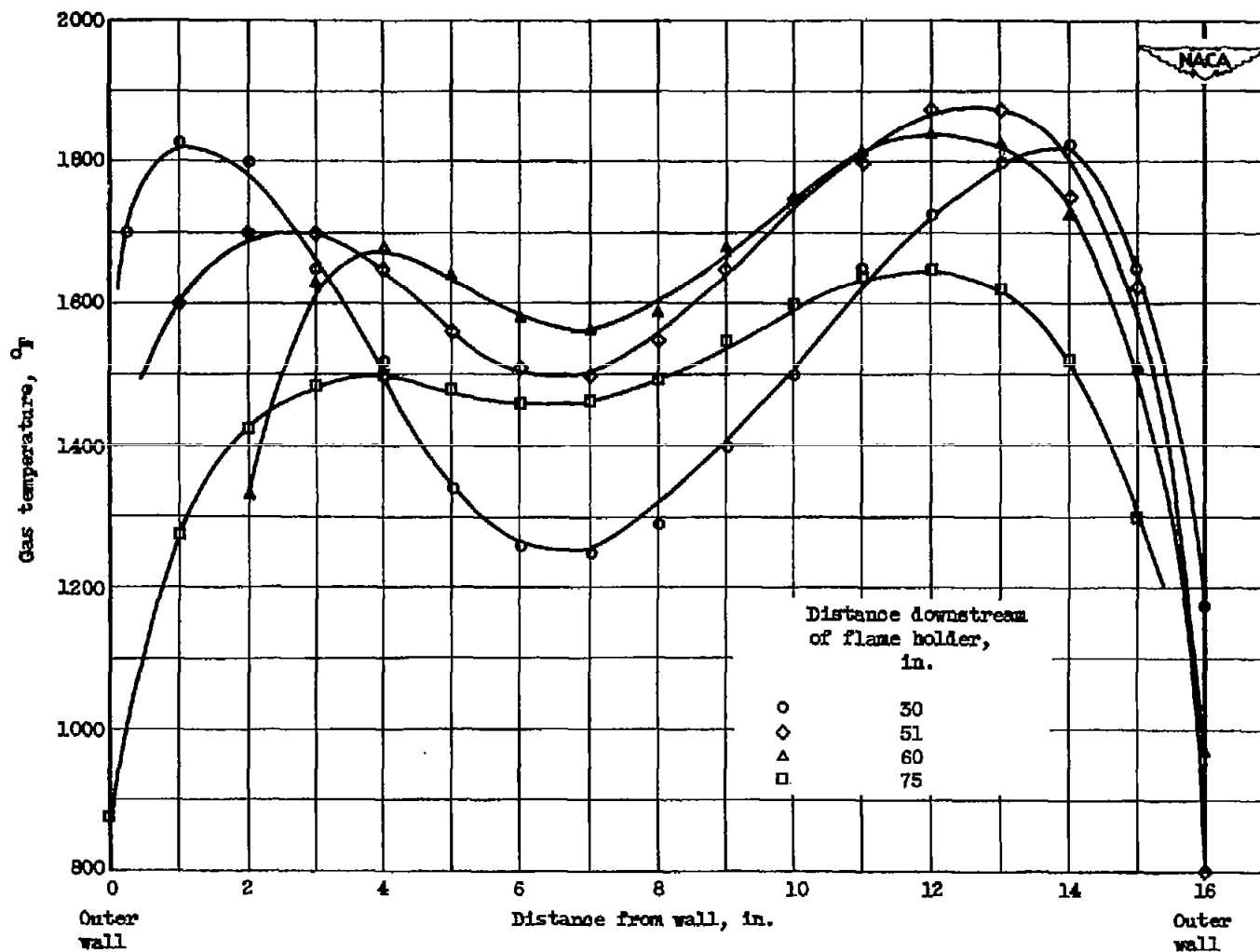


Figure 9 . - Fuel-air ratio distributions midway between two flame holders for MIL-F-5624A grade JP-4 fuel. Over-all fuel-air ratio, 0.017; inlet-air temperature, 600° F; velocity, 230 to 260 feet per second; pressure, 31 to 35 inches of mercury absolute.



(a) Survey stations in wake of flame holder.

Figure 10. - Temperature profiles downstream of flame holder with non-preheated MIL-F-5624A grade JP-4 fuel. Over-all fuel-air ratio, 0.017; inlet-air temperature, 600 $^{\circ}\text{F}$; velocity, 230 to 260 feet per second; pressure, 31 to 35 inches of mercury absolute.



(b) Survey stations in combustion chamber.

Figure 10. - Concluded. Temperature profiles downstream of flame holder with nonpreheated MIL-F-5624A grade JP-4 fuel. Over-all fuel-air ratio, 0.017; inlet-air temperature, 600° F; velocity, 230 to 280 feet per second; pressure, 31 to 35 inches of mercury absolute.

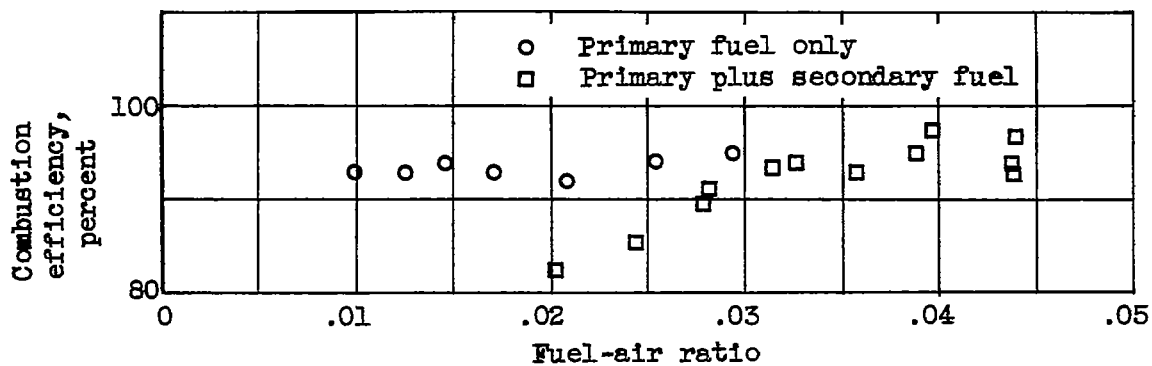


Figure 11. - Combustion performance of sloping-baffle configuration with MIL-F-5624A grade JP-4 fuel. Inlet-air temperature, 600° F; velocity, 230 to 260 feet per second; pressure, 31 to 35 inches of mercury absolute.

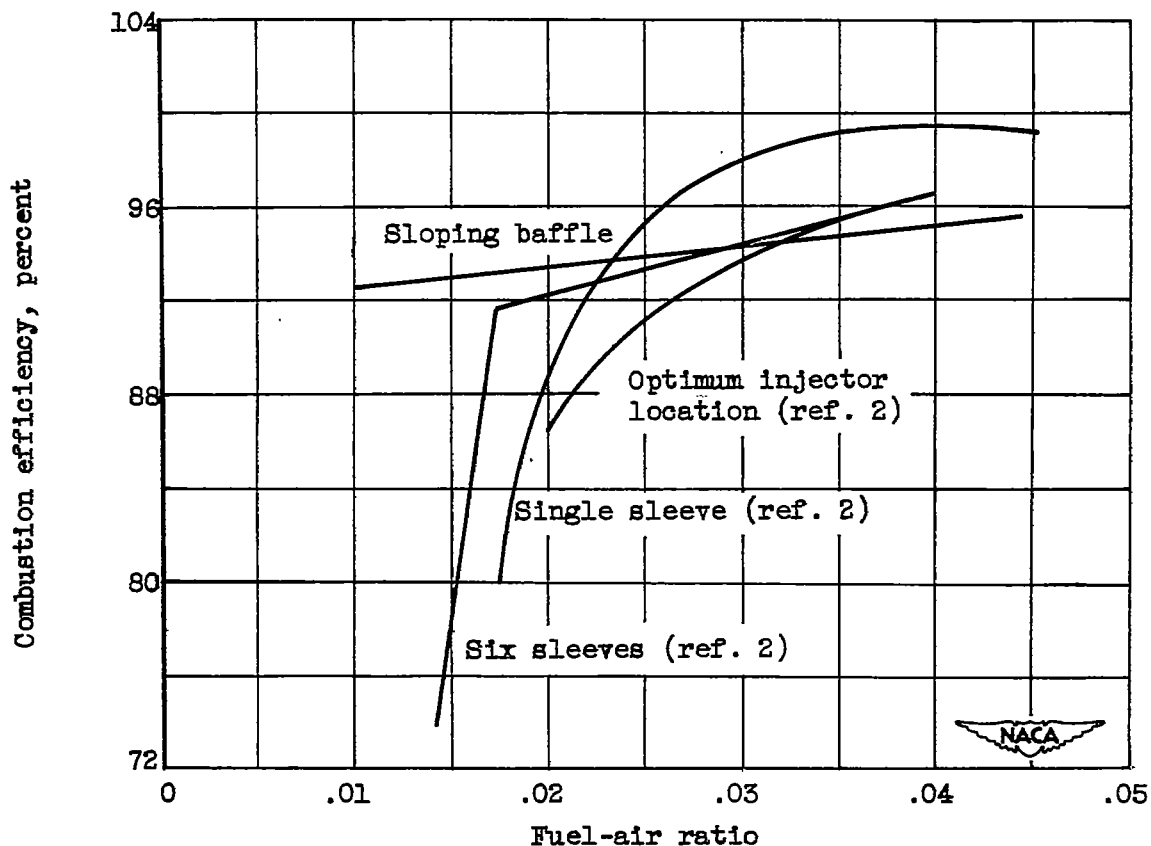


Figure 12. - Summary of combustion performances with MIL-F-5624A grade JP-4 fuel. Inlet-air temperature, 600° F; velocity, 230 to 260 feet per second; pressure, 31 to 35 inches of mercury absolute.

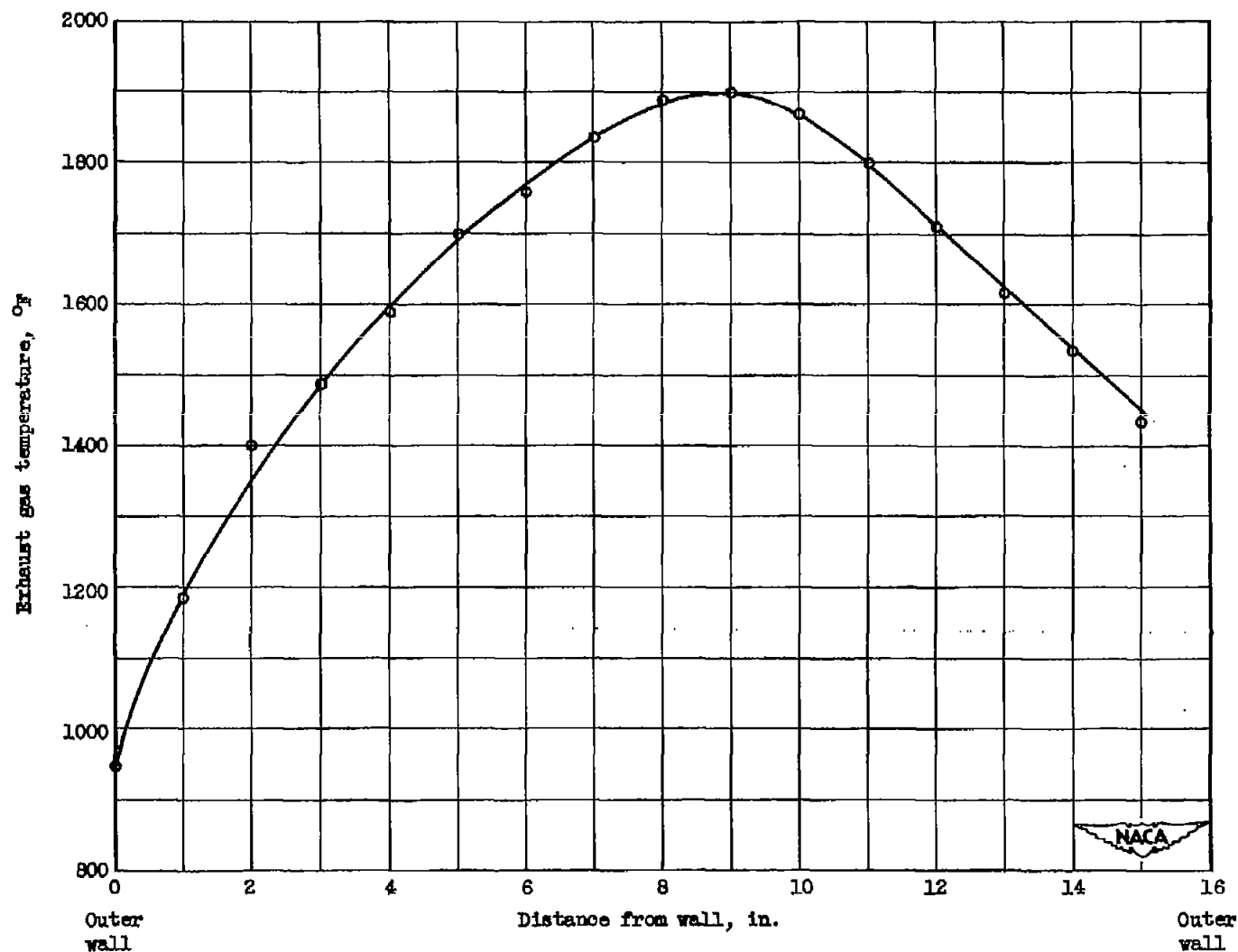


Figure 13. - Temperature profile at combustor exit with sloping-baffle configuration and MIL-F-5624A grade JP-4 fuel. Over-all fuel-air ratio, 0.017; inlet-air temperature, 600° F; velocity, 230 to 260 feet per second; pressure, 31 to 35 inches of mercury absolute.

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